Micro Pump Technology For Spacecraft and Commercial Applications

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Introduction

The principal emphasis in spaceflight technology today is reducing the costs of fabrication, test, launch and operation. This directly translates into the miniaturizing of instruments and spacecraft, lander or penetrator. The days of large, multi-instrumented, billion-dollar robotic spacecraft and labor intensive operations are over. Micro pumps, valves and flow meters were conceived to address miniaturization of the variety of fluid flow control elements on spacecraft or more highly integrated 'sciencecraft'. This paper discusses the evolution of this technology from other MEMS programs, presents a variety of 'space' application scenarios and major terrestrial application areas for micro pumps/valves, which far exceed those of space, and their commercial ramifications.

Derivative MEMS

The derivative MEMS technologies came from a NASA advanced technology development contract with JPL and Northeastern University for the fabrication of nano-g accelerometers (range 10"2 -108 g over 0.0001 -25 Hertz bandwidth) to measure tri-axial orbital dragon the Shuttle and Space Station. [1,2] The specific innovations that led to realization of a robust micro pump where zero thickness waferbonding and encapsulation techniques enabled the intimate joining of two wafer surfaces: intra- and wafer-to-wafer inter-electrical contacting or electrical isolation'; and high force electrostatic 'caging".

In the nano-g accelerometer zero thickness referenced bonds were essential to attain tight spatial tolerancing. A eutectic bonding procedure was developed where etched channels were created in the bond regions (Figure 1) on which a spreading layer of metal was deposited and patterned in the channels. Finally, the bond metal was deposited and patterned on top of the spreading layers in such a way that it protruded above the wafer surface and was narrower than the spreading layer so its volume was less than the volume of the channel. When two dice prepared in this way are brought in contact and heated, the bond metal melts and spreads by wicking and capillary forces, reducing the spacing between the wafer surfaces to zero.

Where contact metals are, or are beneath, the spreading layers, this bonding procedure provides electrical inter-connection between wafers in addition to hermetic sealing. This procedure provides a packaging technique superior to that of micro ball grid arrays or flip chip technology. Indeed it can be adapted to electrical interconnections and thermal management of multi laminated SOI ultra dense 3D circuits. Multi chip carrier modules are rendered obsolete and a whole new procedure for fabricating miniature MEMS/MST electronic hybrids is created.

Figure 1 Zero Thickness Eutectic Bonding

The nano-g accelerometer contained a flimsy proof-mass suspension system and a fragile tunneling tip, both of which required protective, re-deployable electrostatic 'caging' during quiescent handling and high acceleration or shock loading. The innovative 'caging' mechanism consisted of a metal plated force plate die that is covered with an oxide layer (0.5 μm) to prevent an electrical contact between the proof mass and the force plate when the proof mass is being electrostatically clamped.

The electrostatic force relationship is

$$F_c = \frac{\varepsilon_{ox} . A . V^2}{2d_{ox}^2},$$

where ε_{ox} is the dielectric constant of oxide (4x8.85 x10^{-12} Newton/Volt*)
A is area of conductive strip
V is applied voltage
and d_{ox} is the thickness of the LTO (0.5 pm).

Where the distance (d_{ox}) is small, at fractions of a pm, small voltages generate large electric fields of Mvolts/m, which in turn produce significant attractive forces. For larger voltages, the attractive forces increase with the squared function of the applied voltage. The breakdown electric field strength of the insulation layer sets the limit for attainable 'caging' forces.

The relatively large proof mass and force plate do not conform to one another. Surface profiles of the proof mass and force plates indicated that as much as 10 microns of variation were typical on the proof masses. Also, microscopic inspection revealed that small particles were present in the LTO deposition, which prevented the mass from coming into intimate contact with the force plate. The collective effect of the low spatial variation of surface flatness and the LTO particles increase the effectiveplaten gap and thus both the voltage required to hold the proof mass against gravity and the electrical capacitance.

An equivalence model consists of an aggregate of parallel plate, uniform oxide and air-gap spacing capacitors. This equivalence relationship is represented by

$$F_e = \left(\frac{\varepsilon_{air}.\varepsilon_{ox}.A.V^2}{2(\varepsilon_{air}.d_{ox} + \varepsilon_{ox}.d_{air})^2} \right)$$

where ε_{air} is the dielectric constant of air, and
d_{air} is the weighted average thickness of air gap.

As demonstrated small insulation thicknesses of fractions of a μm lead to significant electrostatic forces. Flexible membranes, as deployed in peristaltic pumps, are largely unaffectedly the surface flatness and the LTO particles' separation of rigid platens and thus electrostatic forces are more representative of the theoretically ideal case. Essentially the breakdown electric field strength of the insulation layer sets the limits on pump pressure and pumping rate for an electrostatic peristaltic pump.

Peristaltic

Peristaltic is a form of fluid transport that occurs when a progressive wave of area contraction or expansion propagates along the length of a dispensable tube containing a liquid. Physiologically, peristaltic action is an inherent neuromuscular property of any tubular smooth muscular structure. This characteristic is put to use by the body to propel or to mix the contents of a tube, as in the urethra, gastrointestinal tract and the bile duct.

The following description outlines the mechanisms of a reverse engineered micro peristaltic - type pump[4]. Envision a substrate in which a smooth contoured concave channel has been etched, the whole surface coated with a thin metal layer and, over this metal, a thin coating of insulation material. When an electrically conductive membrane is clamped in intimate contact with the thin insulation layer of two shells (as illustrated in Figure 3) and a voltage is applied to the lower metal layer and the membrane, an electrostatic attractive force pulls the membrane down into the channel. The membrane rolls down the surface of the insulation because the greatest attractive forces are generated where the distance from the conductive strip are smallest (i.e. insulation thickness). Conversely, when a voltage is applied to the

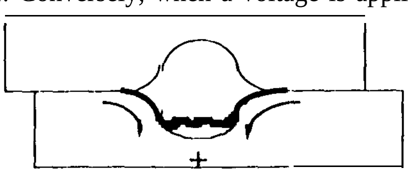

Figure 3. Electrostatic Actuator - Lower Shell

upper metal layer and the membrane, the membrane rolls up the surface of the insulation of the upper channel.

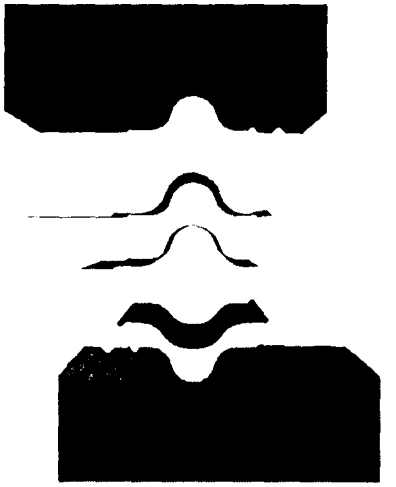

Figure 4. Exploded View Of Micro Peristaltic Pump

Figure 4 presents an exploded diagram of two complementary smooth concave channel pump shells, patterned series of electrically conductive strips, insulation layer, and the flexible electrically conductive membrane. Figure 5 illustrates the assembled micro peristaltic pump where the two substrates sandwich a single membrane between them. A hermetic seal is created by the compression of the membrane and the outer eutectic bond wall.

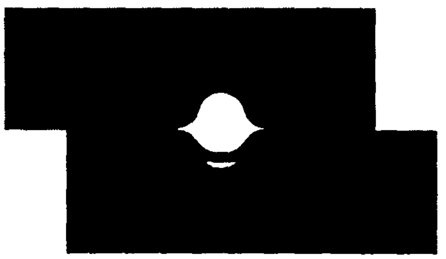

Figure S. Assembled Micro Peristaltic Pump

Earlier the effect of applying voltages to the lower and upper conductive surfaces were discussed. When a suitable voltage between the membrane and each of the conductive strips is applied in succession, the membraneis pulled into the channel and successively along the length of the channel. And, when the actuator elements are connected to the outputs of dual interlaced and interlocked shift registers, the membrane initially flows along the upper channel surface before the membrane is released for several periods (zero), drawn down into the lower channel and along the lower channel surface.

This actuation progression of a membrane "wall" across the composite channel provides a miniature peristaltic pump. Alternate inversions of the bit streams sequences creates multiple membrane "bubbles" that move down the channel (Figure 6), pushing the entrapped fluid in front of and pulling the fluid behind each membrane "wall." The electrostatic actuator has no resistive loss so pump power is only consumed by the membrane, in the compression work function and in circulating the fluids through micro channels.

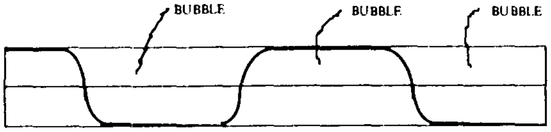

Figure 6. Multiple "Bubble" Peristaltic

This miniature digital peristaltic pump architecture represents a true two-dimensional analog of the three-dimensional peristaltic mechanisms that are endemic in living organisms. It is valueless and impervious to gas bubble entrapment that has plagued other attempts at miniature pumps. Also it does not require priming and can tolerate the adherence of small foreign particles (gracefully degraded) on channel or membrane surfaces. The pump is self-purging, tending to push everything before the membrane in its intimate rolling motion across the channel surface. This basically digital pump can transport fluids or vapors over an extended range of flow rates, is impervious to high mechanical shock or vibration, is a positive displacement flow meter, and can function in a static mode as a valve.

Pump Applications

Spaceflight hardware is made up of two broad categories: the spacecraft, penetrator or lander, and the payload of instruments. The spacecraft engineering functions that are pump or valve related are propulsion, orientation, thermal management and propellant management. Elevation control is relevant for aerobots and thermal management is required for aerobots, penetrators and landers. The instrument functions are thermal management, objective cooling, fluid transport and pressure management.

Propulsion management requires pressure regulation and isolation of both propellant and oxidant. Valve modulation can be used for pressure regulation and fluid isolation can be achieved with low leakage valves. A variant of the peristaltic pump can, if the electrostatic force exceeds supply pressure, provide a fast valving regulator function. And impervious membraned valves can provide

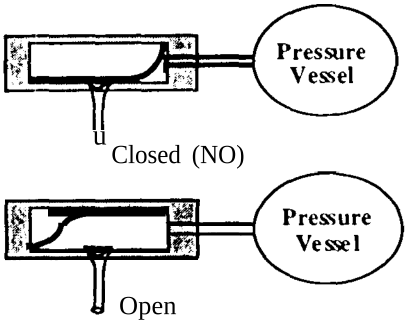

Figure 7 Electrostatic Valve

fluid isolation. The electrostatic flexible membrane valve (see Figure 7) is a normally open device and can only regulate and seal when powered. As the electrical insulation in these valves is very high, current flow and thus power requirements are minute. Hence if power is perpetual as is the case on spacecraft, electrostatic valving is viable.

Terrestrially there is a large and growing need for precisely metered drug delivery systems. The pump insulation layer provides galvanic isolation from pumped fluid, also the insulation and membrane materials can be chemically inert. Miniature peristaltic pumps may therefore be deployed *in vivo*. The beverage industry has need of the metered delivery of essence concentrates. The high cost of exotic chemicals and often the low volumes of chemical or biological samples dictate the need for miniature assay or reactor networks and thus the requirement for miniature valves, pumps and, ideally, flow meters.

In ion propulsion systems small high energy plasmas ionize small volumes of low pressure gas and high electric fields accelerate these ions to high exit velocities, Figure 8 is a cartoon of a honey-comb ion thruster where each cell is a separate ion engine. A miniature peristaltic pump is dedicated to each cell to seal off or provide metered gas flow.

By controlling which engines in the array are operating the honey-comb thruster can provide gimbal-less 'steering'. If some of the peripheral cells are *offset* from the perpendicular then spin control is possible. Finally, the massive redundancy of the array increases the truster's reliability.

Figure 8 Honey Comb Thruster

While ion plasma thrusters have no terrestrial applications, low-pressure high-energy plasmas of various species have applications in semi-conductor fabrication for both erosive etching and chemical doping. Miniature peristaltic pumps can precisely meter various gases into ionization chambers or arrays of small chambers to facilitate the uniform processing of large substrates. Arrays of miniature flow metering pumps may also control the fuel and oxidant feeds to provide uniform heating (and/or oxidation or reduction) for large surface area heat treatments.

Inertial wheels are another technique utilized to maintain the orientation of spacecraft. Figure 9 presents a cartoon of a fluidic reaction wheel that consists of a closed toroidal pump. The angular velocity of the fluid in the peristaltic toroid is increased or decreased to provide the requisite change in angular momentum. In miniature spacecraft multiple concentric 'wheels' could be located at the periphery of silicon disks running in the same or opposite directions, depending on required reaction.

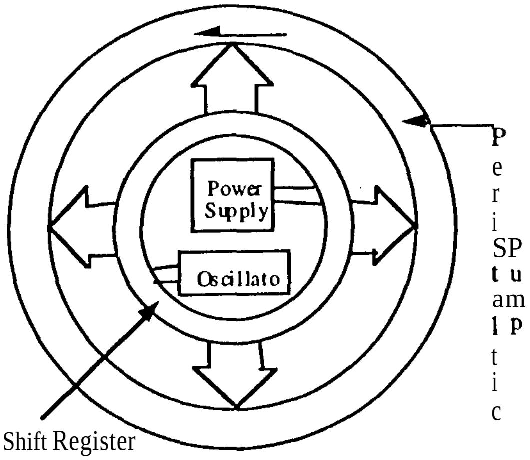

Figure 9 **Fluidic** Reaction Wheel

Effective thermal conductivity of fluid cooling loops are markedly superior to that of the best passive thermal conductive materials. A micro pump may be used to circulate a fluid between a thermal source and sink, effectively transferring heat both within the circulating medium by thermal mass transfer and between the medium and the source and sink by improved convective transfer. Micro channels have large surface area to cross-section ratios, which ensures intimate thermal coupling with forced flow gasses and micro channels.

Shuttle systems and many of the space flight experiments utilize forced convective cooling. The mechanical nature of these cooling systems (fans) makes them the least reliable element in a thermal catastrophic failure scenario. This, and the crew fatigue through exposure to sustained high noise levels, was the impetus for the conception of a MEMS cooler.

Microstructure peristaltic pump channel implementations, complete with substrate imbedded drive electronics, provide high thermal transfer coefficient 'breathing skin'[4]. In a nonvacuum environment such pumps draw from still air at the surface and expel exhaust air away from the surface. The heat pump is not dependent on density gradients and gravity fields, as are convective heat sinks, and is thus space deployable. A small pump-channel cell may be bonded to the surface of integrated circuit chips (see 'hot body' Figure 10) to dissipate their heat directly: no mechanical forced ventilation, no orientation constraints, no noise, and no moving parts.

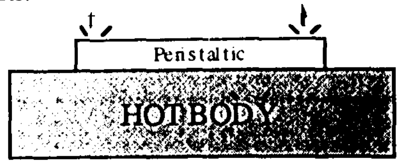

Fig. 10 Forced Convective Transfer Heat Exchanger

With many pump-channel cells per square centimeter large area slabs may be bonded to the surface of power packs or system chassis to remove heat. The mechanical nature of conventional forced cooling systems (fans) for terrestrial electronic equipment also makes them the least reliable element in a thermal catastrophic failure scenario. Fatigue and general discomfort from exposure to sustained noise from the forced cooling of personal electronic equipment (i.e. computers) is a significant issue. A need exists for a reliable, silent and power-efficient means for cooling hot components in consumer and commercial systems that is user friendly, 'green' (smaller packaging) and fiscally attractive (longer life). Such forced convective heat exchangers represent a huge and expanding market.

Thermal transfer capacity is further enhanced by the absorption or dissipation of latent heat generated from gas/liquid, or liquid/gas phase transitions. These phase transitions can be orchestrated by pumping where compression liquefies and expansion vaporizes. The Rankine vapor compression cycle defines such a heat engine. In a micro machined version of a closed loop vapor compression cycle as shown in Figure 11[5], the whole refrigerator, or a serial cascade of refrigerators, may be fabricated from two fused wafers,

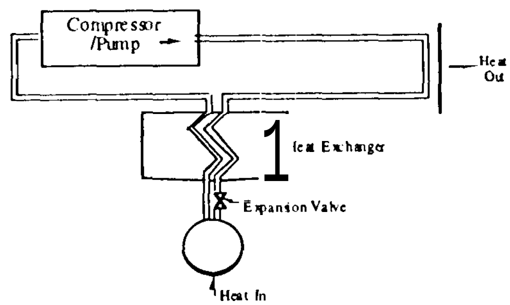

Fig. 11 Phase Interchange Heat Pump Compressor

A miniature peristaltic pump draws refrigerant vapor and compresses it. The gas is then cooled and condensed, the liquid is then cooled by convective transfer into the surrounding substrate micro channel and onto a highly thermally conductive heat exchanger created in the substrate. Another micro channel conducts the cooled liquid refrigerant to an expansion nozzle (valve) in a thermally isolated cold pad where the refrigerant expands into its vapor phase, drawing the latent heat of vaporization from the cold pad. This cold vapor is conveyed in yet another micro channel to the inlet port of the miniature peristaltic pump. The peristaltic pump exhibits very low vibration, as it has no reciprocating parts, but instead has a very low mass membrane that rolls across the surfaces of the channels.

The high thermal transfer capacity of fluid cooling (or heating) loops, and particularly phase change loops, are of significant interest in the thermal management of spacecraft and planetary rovers. In communication satellites, thermal management of individual high energy transmission amplifiers and fast computers are preferredto general electronic 'hot box' management. Another interesting thermal management application is the heating, rather than the more general cooling, of a Martian rover. During daylight, the heat absorbed in solar panels is collected in liquid forced through micro channels in rear of panels. This heat is transferred to, and stored in, thermal capacitors within the rover. In the evening, the heat bank warms the rover's quiescent electronics.

A sophisticated application of a phase interchange heat pump is the cooling of optical instrument's IR imaging objectives, specifically the space based focal plane cooling of a Quantum Well Infrared Photon (QWIP) detector. The QWIP focal plane temperature needs be maintained at 70 K for a heat load of 50-270 mW and a radiator temperature of 200 K. The most efficientcooling cycles are cascaded systems and the most expeditious means of implementing these cycles is the pseudo cascading of mixed gasses in a single[8] expansion process. JPL[6,7] have extended the Russian work on increasing the Joule-Thompson (J-T) cooling power with a variety of gas mixtures.

Figure 12 presents a plot of the temperature-entropy (T-H) diagram for the analysis of a five gas mixture with the high pressure (25 PSI) enthalpy data represented by 'squares' and the dotted best-fit curve and the low pressure (5 PSI) enthalpy data represented by the 'circles' and dashed best fit curve.

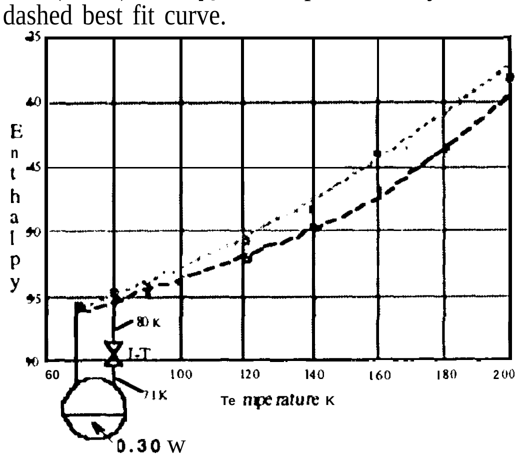

Fig. 12 T-H Diagram For Selected Gas Mix

A preferred embodiment of a focal plane cooler would incorporate the whole system on two bonded (4" dia.) silicon wafers. The radiators would occupy the outer rim (0.75" both sides), the pump (pumps) and interchanger (interchangers) would be inboard and the 2 x 2 cm cold pad would be in the center. Using silicon as the substrate for the cooler has several advantages: the pump electronics can be incorporated directly into the substrate, silicon exhibits high thermal conductivity (particularly at low temperatures) and its micro machining chemistries and characteristics are mature. For space applications it may be prudent to have redundant pumps as a reliability measure, should a micro channel become blocked or a particular pump fail. Miniature pressure and temperature sensors could also be incorporated around the various micro channels to provide health monitoring and efficiency optimization capabilities.

Convective coupling between forced flow gasses and micro channel surfaces are high and channel surface area, relative to cross section, increases as dimensions decrease. The thermal conductive loss across thin silicon partitions between neighboring channels are also small particularly when these channels are contained within insulated silicon bridges. Such thermally isolated micro channel structures are very efficient heat exchangers.

The peristaltic pump is also a micro channel that can exchange compression heat with a neighboring channel to approach the efficiency of an isothermal compression cycle. The compression profile of a peristaltic pump is determined by the diminishing thickness profile of the actuator strips. For an ideal pump the step volume profile would be matched to the effect iveratio of specific heats (y) of the gas mixture and thermal gradient down the pump. Once this profile was determined, the photo lithographic masters can be computer generated with the required actuator spacings.

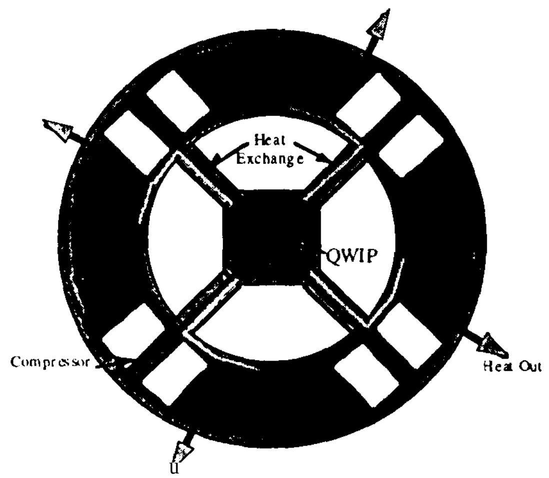

Fig. 13 Wafer Cryo Cooler and Detector Mount

Were the complete cryo cooler fabricated out of two 4" diameter silicon wafers (see Figure 13), the total mass would be 35 grams, and with etched out bridges and non-utilized areas this mass would be less than 25 grams. A single peristaltic pump would weigh less than a gram. The J-T expansion valves would be just inboard of the focal-plane thermal insulation bridges where the parasitic heat loads would be balanced and the low pressure return conduit would pass back along the same bridge to cool the high pressure gas feed.

A second multi-gas mixture and pseudo cascade single expansion cooler was designed that would operate between 190 and 330K. This cooler, when operated in series with 70-200K cooler, provides a terrestrial cryo-cooler for QWIP. Terrestrial interest in QWIP detectors is for thermal tomography but there is a huge automotive market for actively cooled long wave IR detector arrays for night and harsh weather vision enhancement. The extremely low vibration, low power, small size and robust nature of the preistaltic pump make it ideal, in a closed loop multi gas single stage format, for automobile and hand held applications. The clock speeds of high performance computers are limited by their operational temperature. Several orders of magnitude increase in clock speed have been demonstrated with cryo cooled processors. Miniature cryo cooler loops would boost the performance of computation, graphics and communication processors - a growing contemporary market.

The reason for sending rovers, aerobots and penetrators to planets is to gain ground truth for the remote measurements of orbiters and telescopes. Atmospheric gas species and abundance are one such measurement class requiring a miniaturized gas analyzer or mass spectrometer. Figure 14 presents a cartoon of a miniaturized gas analyzer, conceived for use on the next generation Mars rovers, that incorporates all the components and operates under the same physical principles as conventional equipment. The instrument incorporates a miniature peristaltic pump, a wavelength resolving spectrometer and a gas excitation chamber[10]. The pump continually draws and regulates the pressure of gas into the excitation chamber where it is ionized by a unique miniature plasma generator. Light emitted by the ionized gas is directed toward the miniature Fabry-Perot interference spectrometer and detector.

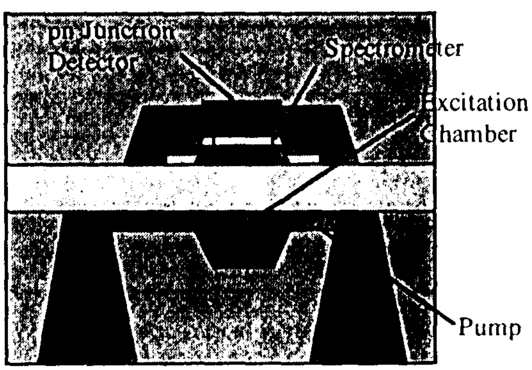

Fig 14 Schematic representation of micro gas analyzer

The terrestrial applications for micro-gas analyzers are immense. For example the monitoring of buildings to establish and control air quality and ensure they are not 'sick'. Or to monitor the environments of ground transportation vehicles and airplanes. Another large application arena is for the monitoring of domiciles and automobiles for toxins and carbon monoxide, or the monitoring of water for pollution markers such as methane, ammonia, alcohols, keytones and urea. Even more personal analyzers might be used to monitor allergies and smog levels; as breath analyzers for intoxication determinations; and even as breath odor quotient detectors.

Acknowledgments

The work described was performed at the Jet propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration. The author would like to thank Prof. Paul Zavracky of Northeastern University for his collaboration on the nano-G accelerometer, and for his and Prof. Jeffrey Hopwood's contributions in the conceptional development of a miniature gas spectrometer. Jack Jones' contributions in determining the gas mixtures for micro cryo cooler are also acknowledged.

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